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Experimental study on aerodynamic characteristics of high-speed train on a truss bridge: A moving model test

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ABSTRACT

To address the common issues and deficiencies associated with state-of-art static and moving train wind tunnel test, this paper devised a novel test system for the aerodynamic test of vehicles travelling across the bridges. A servo motor synchronous driving system was used along with a wireless module for the transducer in measuring aerodynamic forces on the high-speed train. The maximum speed of the train model can reach 15 m/s with an effective acquisition time of 0.7s. Besides, due to the independent arrangement between the bridge model and the test motion driving system, replacement of the bridge model can be achieved, enhancing the adaptability of the system. Based on the developed test system, a scaled model (including a steel-truss bridge and the CRH3 train system) was tested and aerodynamic characteristics of the moving train were measured and analyzed under various wind velocities, speeds of the train, and wind angles. It reveals that aerodynamic coefficients of the train measured with a static train model are different from those measured with the dynamic train model. The existence of truss bridge causes that the aerodynamic coefficients of model train vary significantly as the incoming wind velocity, speed of the train, and wind angle change.

1. Introduction

When a high-speed train is travelling under a crosswind environment, its aerodynamic drag forces and other aerodynamic stability parameters such as the lift and side forces and rolling moment are significantly changed. The variation of these aerodynamic parameters can cause train derailment and flip over or even more disastrous accidents (Baker and Reynolds, 1992; Schetz, 2001). In addition, when the train is travelling across a bridge, the turbulent crosswind flow affected by structures such as bridges and towers can also have a significant impact on the aerodynamic characteristics of the train (Chen and Cai, 2004; Guo and Xu, 2006; Li and Ge, 2008; Han et al., 2014). Therefore, analysis of such influences on the aerodynamic stability of modern high-speed trains becomes necessary and essential.

In general, full-scale measurements, wind tunnels and computational fluid dynamics (CFD) models are the major techniques in estimating the aerodynamic characteristics of high speed trains. Baker et al. (2014), Soper et al. (2017) and Rocchi et al. (2018) adopted the actual line train to study the aerodynamic environment caused by the train movement; however, the natural wind is easily subject to variation and difficult to maintain a certain wind speed level for a period of time, which is essential for aerodynamic force test of train under crosswind. Therefore, the full-scale measurement is rarely used in estimating the aerodynamic forces of the train under crosswind. Alternatively, computational fluid dynamic (CFD) simulations play a significant role in evaluating the aerodynamic performance of the train. García et al. (2015) and García et al. (2017) employed a CFD model (with a scale of 1:1) to study the effect of turbulent wind on aerodynamic characteristics of the train. Zhang et al. (2016) and Wang et al. (2018) investigated the aerodynamic performance of a high speed train with moving ground and rotating wheels conditions relying on the CFD models. Cheli et al. (2011), Wang et al. (2014) and Premoli et al. (2016) used the dynamic mesh method to model the effect of relative movement on aerodynamic characteristics of railway vehicles. Such numerical studies have achieved a good agreement with the test results by wind tunnel; However, strict requirements on numerical model grid in matching with the wind tunnel test and extensive computational cost make such numerical simulation mostly focus on the aerodynamic characteristics of trains with simple infrastructures (like the flat ground and embankment), rather than on the aerodynamic simulation of moving trains with complicated structures

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such as bridge structure. Overall, the wind tunnel test is the most widely used technique considering both time and accuracy of the aerodynamic results.

The wind tunnel experiments are commonly performed for either the static or moving trains. There are two major issues in using a static train model to simulate the surrounding wind environment of the moving train. The first issue is that the test set-up requirement using a static train model inevitably causes the change of actual yaw angle on the bridge structure. More specifically, as seen from Fig. 1, the bridge and train are under the wind loading with a wind angle of α and incoming wind velocity of U. Due to movement of the train, the actual angle of the wind relative to the train is the yaw angle β and the relative wind velocity is the V_{res}. Therefore, the test model should be rotated to an angle of β and the wind velocity should be set as V_{res} when using a static train model to simulate the wind environment around the train. Such method can satisfy the aerodynamic requirements of the train model but results in modelling angle between the wind direction and bridge being β. However, the actual angle between the wind direction and bridge was changed from α to β and the airflow profile around the bridge cannot be realistically simulated in the static test, resulting in an inaccurate estimate of aerodynamic characteristics of high-speed train travelling across the bridge.

The second is the issue regarding the boundary layer. As seen from Fig. 2(a), unlike the natural wind, the air flow resulting from the movement of the train relative to the air does not exhibit as a boundary layer in the track plane. While in the wind tunnel test for the static train model, the simulated flow is a resultant boundary layer from the moving air flow generated by train movement and the natural wind, as seen in Fig. 2(b). Comparing with the realistic wind profile of Fig. 2(a), using the boundary layer input of Fig. 2(b) could result in an incorrect wind velocity profile, and consequently lead to inaccurate aerodynamic forces and coefficients. Existing techniques such as the moving plate, boundary layer suction, and tangential incident method had been proved effective in reproducing the actual boundary layer for the moving train to some extent (Hucho, 1993; Wiedemann and Potthoff, 2003; Wickern et al., 2003); however, such methods are difficult to be implemented in wind tunnel laboratories.

Due to the deficiencies associated with wind tunnel test using static train, various types of wind tunnel experiments using moving train model have been proposed. Although such experiments can simulate realistic wind conditions around the train, issues such as motion driving mode of the train and stability of the moving train model (due to movement induced vibration of the test devices) should be considered and addressed (Schetz, 2001).

In the moving train experiment by Baker (1986), a device with a trail car was used to drive the movement of the train. The trail car has elastic ropes on both sides and the movement of the train was achieved by regulating the elastic ropes. Such experiments have produced relatively good results; however, this type of movement-driven device requires long guideway for train acceleration and deceleration. Since velocity control was difficult, operating the train at a constant speed level was a challenge. In addition, the device became ineffective after the rope was used for a period of time in regulating the movement. And the open slot in the guideway, which was used in the experiment by Baker (1986), can impact the airflow under the train. Considering the adverse impact of this open slot, Baker (1986) proposed several alternative improvements to weaken its adverse impact for the future research. To reduce effects of open slot on the airflow characteristics under the train, Howell (1986) devised a bias connector to support the train model and placed the open slot on the leeward side of the train.

U-shaped guideway was used by Bocciolone et al. (2008) and the acceleration and deceleration processes were achieved through the gravity of the train. The device is able to simulate the train operating conditions effectively, especially for flow under the train. However, it has several limitations such as the train model cannot run steadily and continuously at a constant speed (that the train model can only run at low speeds) and model must be reset manually due to the safety of the device (that the efficiency of the experiment was reduced).

Servomotor and synchronous belt drive modes have been used to achieve a better control of the train velocity (Li et al., 2014). However, the guideway was placed on the bridge model, resulting in the load equilibrium issue and the difficulty in distinguishing the aerodynamic load caused by track irregularities and vertical inertial force (Gawthorpe, 1994). To address the particular issue, the bridge should be fabricated with a high degree of flatness to guarantee the smoothness of the guideway, demanding for more rigorous fabrication process of the bridge model which is difficult to achieve.

Dorigatti et al. (2015) explored an innovative physical model to examine wind-induced forces and pressures on a 1:25 scale Class 390 Pendolino model. The train rig can actuate the vehicle model at a speed up to 75 m/s along the straight track with a length of 150 m. To enable the moving model test under crosswinds, a crosswind generator was implemented with an open-circuit perpendicular to the track. It should be noted that the mechanical propulsion system is achieved through the pre-tensioned elastic bungees, which cannot effectively keep the speed of the model train being constant within the entire test section. In addition, this moving rig is more suitable to the aerodynamic test of moving train on the track rather than on the bridge structure.

Yang et al. (2016) devised a promising moving model rig for test model with a large scale ratio (greater than 1/8) and to achieve the accelerating closing to the real Mach number. The rig is capable of accommodating one or two train models simultaneously and was used mainly in studying the aerodynamic structural optimization of the train, aerodynamic effect as a result of the travelling meet of two trains, as well as the evolution of pressure on both tunnel wall and train surface as the train is passing through the tunnel. However, such test rig cannot be easily adopted into a wind tunnel due to the larger scale of the test rig comparing to the usual size of a wind tunnel.

A novel moving vehicle wind tunnel device has been developed by

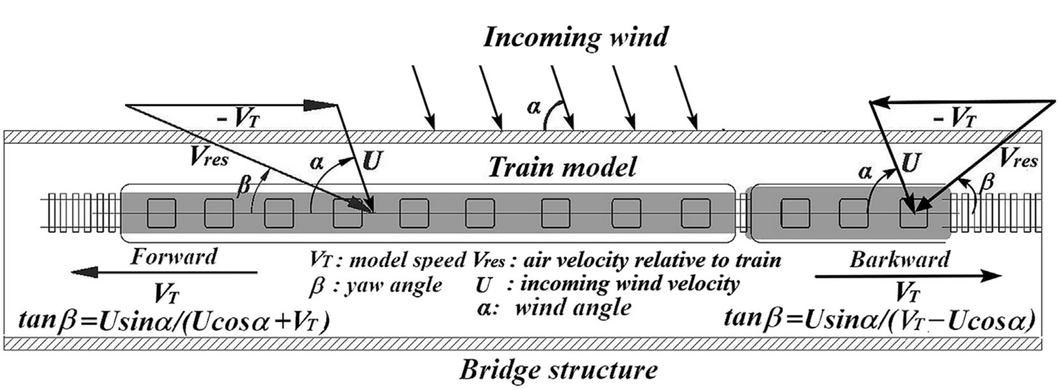

Fig. 1. The wind environment around the bridge and moving train.